

EXPERIMENTAL CHARACTERIZATION OF AN AUTONOMOUS POWER UNIT EQUIPPED WITH A PEM FUEL CELL

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SUMMARY

The paper presents a developed test facility, equipped with a Digital Signal Processor (DSP), for the experimental characterization of an autonomous Auxiliary Power Unit (APU), which is based on a Proton Exchange Membrane (PEM) fuel cell and a set of electrochemical batteries, both connected to a common AC bus through power electronic converters. The paper also describes a steady state model for the simulation of the APU; the model is specifically tuned for a 4.8 kW commercial PEM fuel cell by means of experimental data acquired by the test facility.

1 INTRODUCTION

Proton Exchange Membrane (PEM) fuel cells are potentially suitable for the application in autonomous Auxiliary Power Unit (APU) and various schemes of fuel cell/battery power sources have been recently investigated [1-13].

In a previous study of the authors [14], a preliminary procedure for the sizing of the APU components and for a first identification of the operation rules of the fuel cell (FC), taking into account the stochastic nature of load demands has been presented.

This paper is devoted to the description of a test facility, developed, at the DIEM Laboratories of the University of Bologna, for the experimental characterization of an APU for on-board applications, composed of a commercial grid-connected PEMFC and a battery. Both fuel cell and battery are connected to a common AC bus through power electronic converters.

Moreover, the paper describes an empirical steady state model developed to reproduce and monitor the FC operation and to evaluate the FC system performances. The model could be used for the system components optimization, for example if a fuel cell unit is given, while the main auxiliaries are to be established in order to maximize the system electric efficiency.

The outline of the proposed paper is the following: Section 2 briefly describes the considered APU and section 3 describes the experimentally developed test facility with the implemented sensors and DSP system features. Section 4 shows the characteristics of the conceived fuel cell model, highlighting the experimental data acquired with the test facility and required by the model.

2 ARCHITECTURE OF THE ENERGY SYSTEM

The APU in study is aimed at feeding both Alternating Current (AC) and Direct Current (DC) power requests, which could occur in typical applications of an APU.

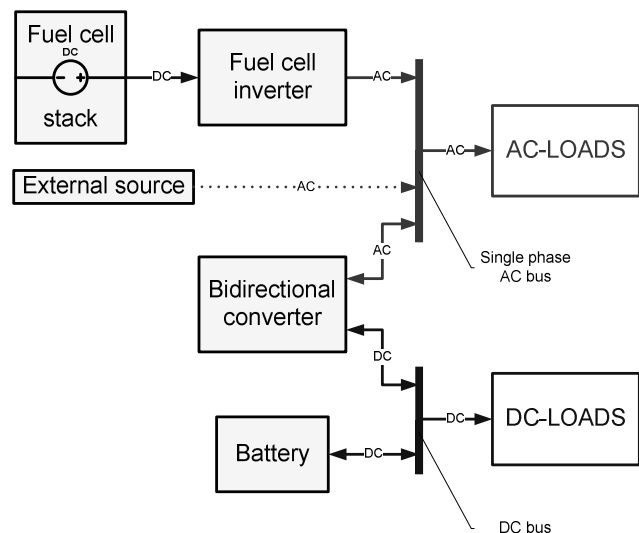


Fig. 1. Electric connections of the energy sources to a common AC bus.

Figure 1 provides the layout of the considered hybrid power system: the main energy source is a PEM fuel cell, which is fed by a gaseous hydrogen storage subsystem and generates an output variable DC electric power; the fuel cell DC power is

converted in AC power by means of a dedicated FC inverter. Moreover, the system includes a battery storage unit; the possibility to use an external AC power source, when available, is also considered. The key component is the bidirectional converter, shown in Fig. 1, which allows the interconnection between FC and batteries to a common AC bus. The common AC bus configuration has been privileged, with respect to the case of a DC common bus configuration, in order to reduce the mutual interference between the two energy sources (FC and battery), which have different voltage/current characteristics. The external source (e.g. the power distribution network), when available, feeds the same AC bus. If the connection with the external source is not available, the bidirectional converter operates as voltage and frequency source.

Therefore the power system can operate in the following three different conditions:

1. Stand-alone mode with load requests that overcome fuel cell output: both the FC and the battery generate power.
2. Stand alone mode with load requests lower than fuel cell output: the battery bidirectional converter operates as a battery charger, still controlling the AC bus voltage; in such a configuration the bidirectional converter becomes an additional load fed by the fuel cell.
3. Grid connected mode: the battery bidirectional converter works as battery charger with the fuel cell normally switched off.

An APU specifically designed for on-board application has been considered in developing the test facility; the full system takes into account a commercial PEM power system, an acid-lead battery and a bidirectional voltage-source converter. The main characteristics of the APU components are summarized in Table 1.

Table 1: components characteristics

	Rated output value	Additional comments
FC PEM system	4.8 kW	grid connected
Battery	100 Ah	48 V _{DC}
Bidirectional converter	4.2 kW	Voltage source converter

The balance of plant of the FC power system shown in Fig. 2 consists of:

Hydrogen line

- A hydrogen pressure reducing valve, which reduces the inlet H₂ pressure, to the FC required value equal to 1.8 bar;
- a safety electro valve;
- a purge dead-end valve, operating with a pulsing logic to evacuate the water vapour and other inert gasses at the anode side.

Air line

- A inlet air filter;
- a variable speed air blower, admitting external air at the cathode side with a pressure value of 1.2 bar;
- a gas to gas humidifier, which humidifies the inlet air stream by using the water vapour produced by the

hydrogen oxidation. The humidification process requires neither electric energy nor heat from external sources.

Cooling subsystem:

a) Liquid line

- Water tank, collecting distilled water;
- water pump, required for water circulation in the cooling line;
- a directional valve, used to control the water temperature depending on the system operating conditions, by regulating the water flow into the heat exchanger, in order to keep the stack internal temperature within the range 60 - 70°C;
- a plate heat exchanger, for heat transfer to an external fluid (water in Fig. 2) for low temperature cogeneration purpose;

b) Air line

- A cooling fan, which removes residual heat from the fuel cell system.

Electrical equipments

- Fuel cell inverter, which provides AC power at 230 V from fuel cell DC power input;
- auxiliary voltage transformer, reducing the rated 230 V in AC to 24 V in AC required by the control board;
- auxiliaries control board, feeding the auxiliaries in DC.

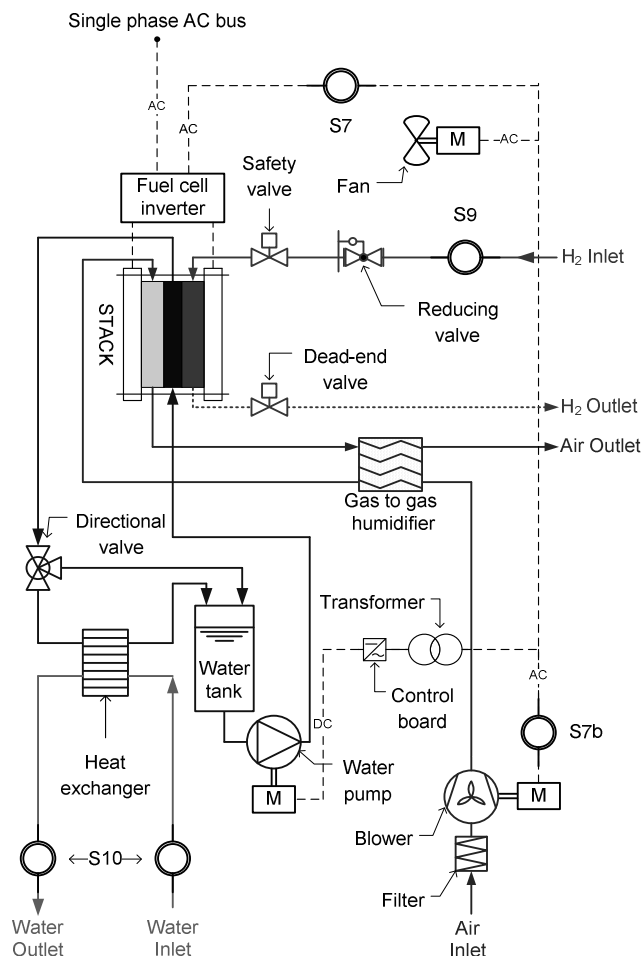


Fig 2. PEM fuel cell layout and auxiliaries.

Table 2: FC auxiliaries power absorption

Auxiliary	Consumption at maximum FC output
FC inverter	650 W
Blower (AC)	500 W
Fan (AC)	35 W
Water pump (DC)	25 W

3 EXPERIMENTAL TEST FACILITY

The layout of the test facility developed to study the APU is shown in Fig. 3, where the installed sensors are highlighted; in particular, Hall effect voltage transducers have been used: sensor S1 measures v_{AC} the FC inverter output voltage, S2 is used for v_{Aux} the voltage at the auxiliaries and sensor S3 measures V_{DC} the DC voltage at the FC output. Hall effect current transducers have been used: S4 to measure i_{AC} the FC inverter output current, S5 for i_{Load} the current at the load and S6 for i_{net} the AC current at the external network. Sensor S7 is a current probe which measures the value of auxiliaries current i_{Aux} , while the current probe S7b shown in Fig. 2 measures the current absorbed by the blower i_{Blow} ; another current probe S8 is used to measure the FC-stack output DC current I_{DC} . The hydrogen consumption is measured by means of a thermal flow meter (S9 in Fig. 2), while a thermocouple is used to obtain the temperature difference ΔT_W between the inlet and the outlet stream of the external water (S10 in Fig. 2).

The characteristics of the different implemented sensors are reported in table 3.

Table 3: sensor characteristics

Sensor	Type	Accuracy	Measured quantity
S1	LEM LV25-P voltage transducer	$\pm 1.6\%$ (rdg)	v_{AC}
S2			v_{Aux}
S3			V_{DC}
S4	LEM LA100-P current transducer	$\pm 0.45\%$ of rdg	i_{AC}
S5			i_{Load}
S6			i_{net}
S7	LEM PR200 current probe	$\pm 1\%$ of rdg ± 0.03 A	i_{Aux}
S7b			i_{Blow}
S8	LEM PR630 current probe	$\pm 1\%$ of rdg ± 0.5 A	I_{DC}
S9	Bronkhorst H2 thermal flow meter	$\pm 0.8\%$ of rdg $\pm 0.2\%$ of full scale	\dot{V}_{H_2}
S10	K-series thermocouple	± 1 °C	ΔT_W

The test facility includes a Data Acquisition device (DAQ in Fig. 3) that receives measured data (at 10 kSa/s in asynchronous mode) from all the sensors S1-S10 and stores data (every 200ms) for future analysis. The DAQ board is a

National Instrument PCI-6024E DAQ with 12bit resolution and a maximum sample rate of 200 kSa/s [15,16]. The signals coming from sensors are connected to the DAQ using a National Instrument SCB-68 shielded I/O connector block. The acquisition software has been developed using National Instrument Labview 8.0.

A Digital Signal Processor (DSP) based on dSpace DS-1104 unit, equipped with a double master/slave processor MPC8240 (a core-PPC603 250 MHz-CPU 64-bit floating-point processor) [17] is used to control the test facility operation. The dSpace DSP software has been developed using Matlab-Simulink

The DSP receives measures from sensors S1, S4, S5 and S6; these data are used by the DSP to evaluate the real-time state of the system; moreover the DSP controls the circuit breakers (BES, BB, BFC and BFL in Fig. 3) installed for over-current protection and for the modification of the system configuration.

A variable electric load simulator has been developed to reproduce different load scenarios and profiles. The load simulator unit is composed by a 9 Ω resistor and 12 mH linear reactor, each one connected to the AC bus through an On-Load Tap-Changer (OLTC) transformer (see Fig. 3). The OLTC is characterized by 400 tap positions, each corresponding to a 0.25% variation of the no-load rated voltage (230 V). As shown in fig. 3 the OLTCs are under the control of the DSP, which modifies the OLTC positions, in order to change the amount of active and reactive power loads.

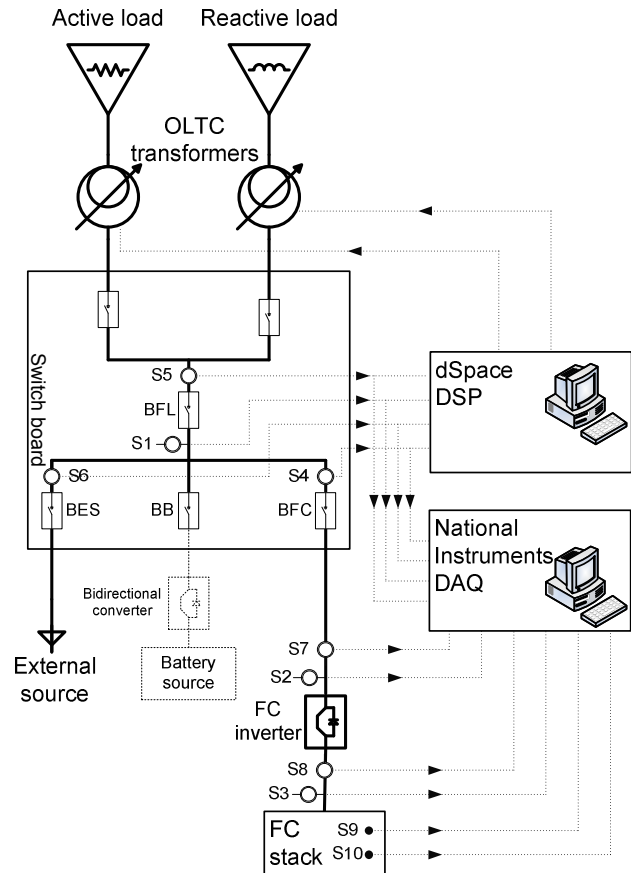


Fig. 3. Test facility scheme.

4 FC SYSTEM STEADY STATE MODEL

A steady state model has been developed in Matlab-Simulink for the assessment of the system performances with particular reference to the monitoring of the PEM operation. The model is based on experimental data acquired with the test facility. By means of the quantities measured by the sensors of Table 3, the main fuel cell operating characteristics have been calculated by the DSP using the following equations, where T is the sample time window (200ms).

Stack DC electric power output:

$$P_{DC} = V_{DC} \cdot I_{DC}$$

Active power delivered to the AC common bus:

$$P_{FC} = \frac{1}{T} \int_0^T v_{AC}(t) \cdot i_{AC}(t) \cdot dt$$

Auxiliaries (excluding the FC inverter) active power request:

$$P_{Aux} = \frac{1}{T} \int_0^T v_{Aux}(t) \cdot i_{Aux}(t) \cdot dt$$

Inverter losses:

$$P_{Inv} = P_{DC} - P_{FC} - P_{Aux}$$

Blower active power request:

$$P_{Blow} = \frac{1}{T} \int_0^T v_{Blow}(t) \cdot i_{Blow}(t) \cdot dt$$

A test campaign has been performed in order to obtain the above listed quantities for the full operating range of the fuel cell power output. In this way a set of look-up tables, shown in Figures from 4 to 6, representing the steady state operation of the fuel cell system, have been obtained.

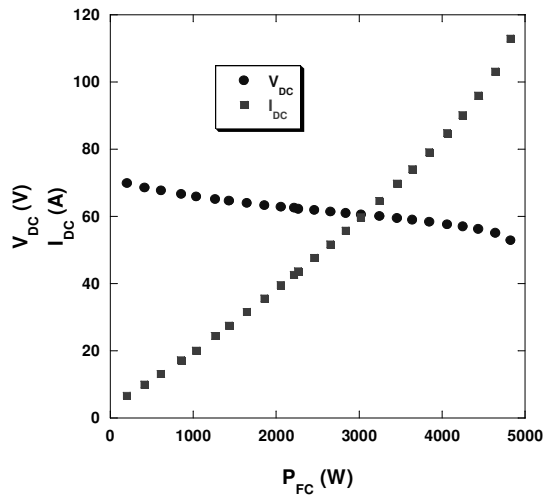


Fig. 4. Fuel cell DC voltage and fuel cell DC current versus fuel cell AC power output

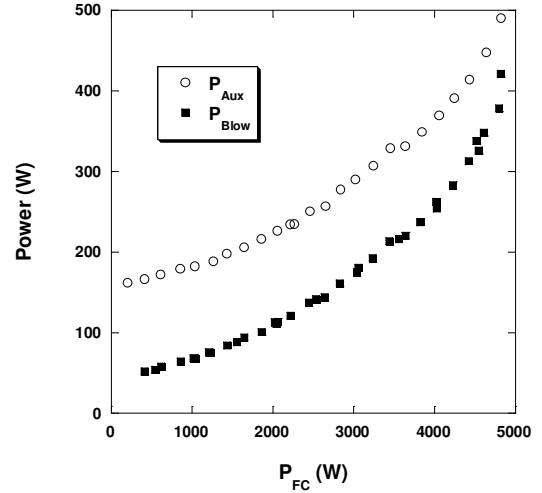


Fig. 5. Auxiliaries power absorption versus fuel cell AC power output

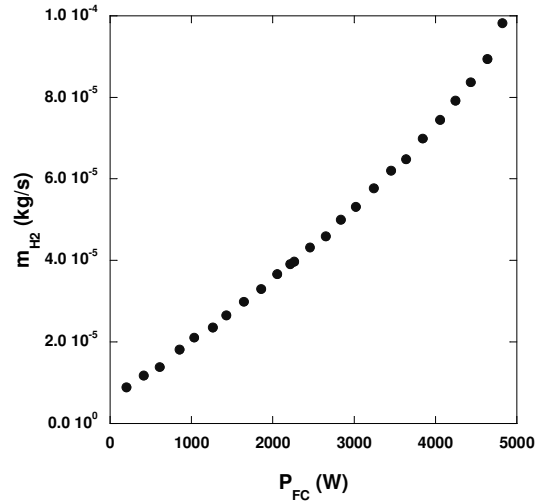


Fig. 6. Fuel consumption versus fuel cell AC power output

This set of plots has been assumed as a reference for the steady states of the system and it has been implemented in the model. By means of the quantities stored in the look-up tables, the model is able to calculate the following performance parameters.

The fuel cell system efficiency:

$$\eta_{TOT} = \eta_{DC} \cdot \eta_{Inv} \cdot \eta_{Aux} \cdot U_{H_2}$$

where η_{DC} is the stack efficiency, η_{Inv} is the inverter efficiency, η_{Aux} is the system auxiliaries efficiency and U_{H_2} is the fuel utilization factor.

The stack efficiency, calculated with:

$$\eta_{DC} = \frac{V_{DC}}{V_{LHV}}, \quad V_{LHV} = \frac{LHV \cdot mw_{H_2} \cdot n_{cells}}{2F}$$

where LHV_{H_2} is the hydrogen lower heating value considered equal to 120 MJ/kg, mw_{H_2} is the hydrogen

molecular weight, assumed equal to 0.002 kg/mol, F is the Faraday constant (96485 C/mol) and n_{cells} is the stack number of cells.

The inverter efficiency, calculated as:

$$\eta_{Inv} = \frac{P_{FC} + P_{Aux}}{P_{DC}}$$

The system auxiliaries efficiency:

$$\eta_{Aux} = \frac{P_{FC}}{P_{FC} + P_{Aux}}$$

The hydrogen utilization factor:

$$U_{H_2} = \frac{I_{DC} \cdot mw_{H_2} \cdot n_{cells}}{2F \cdot \dot{m}_{H_2}}$$

where \dot{m}_{H_2} is the inlet hydrogen mass flow rate.

Finally the model provides the air utilization factor according to the following equation:

$$U_{Air} = \frac{\dot{m}_{Air} / \dot{m}_{H_2}}{(\dot{m}_{Air} / \dot{m}_{H_2})_{st}}$$

where $(\dot{m}_{Air} / \dot{m}_{H_2})_{st}$, equal to 34.78, is the stoichiometric air-hydrogen mass flow ratio and \dot{m}_{Air} is the air mass flow rate, calculated as:

$$\dot{m}_{Air} = \frac{\dot{V}_{Air} \cdot mw_{Air} \cdot p_{Air}}{R \cdot T_{Air}}$$

The quantity \dot{V}_{Air} is the volumetric air flow rate produced by the variable speed blower. Figure 7 shows the characteristic curves (continuous lines) for different rotational speed values of the blower used in the considered fuel cell system, while the dotted lines represent the constant efficiency curves.

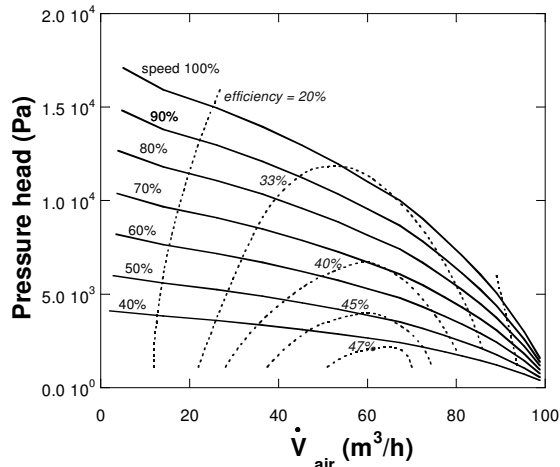


Fig. 7. Characteristic curves of the air blower

Figure 8 shows the block diagram of the implemented model which uses the fuel cell AC output power as input variable and additional quantities, namely the inlet air temperature, pressure and relative humidity (T_{air} , p_{air} , RH_{air}) and the stack number of cells (n_{cells}) as boundary conditions. Once the FC net electrical power is given, then the expected system performances are estimated by the model; in particular, the output quantities shown in Fig. 8 and representing the FC steady state operation, are calculated. The estimated values of the output variables are obtained on the basis of the above introduced equations and the look-up tables shown in Figures 3-7.

The model has been developed in order to reproduce the expected FC behavior, so that it is possible to monitor when the fuel cell operates out of the reference condition; therefore, the model can be also used for diagnostic purposes in order to identify component failures or aging effects.

Since the FC performances are strictly related to the experimental data used by the model, different results can be obtained modifying the values stored in the look-up tables.

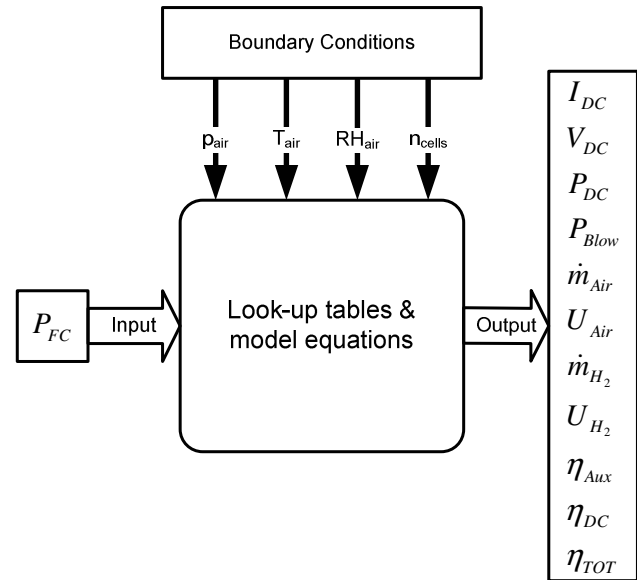


Fig. 8: flow chart of the FC system steady state model

5 CONCLUSIONS

The paper describes the development of a DSP-controlled test facility for the experimental characterization of an APU which includes a PEM fuel cell and a set of electrochemical batteries, both connected to a common AC bus through power electronic converters. The considered architecture, based on the independent connection of all the power sources to a common AC bus, allows the straightforward coupling between electrochemical sources (as the PEM fuel cell and the batteries) with different voltage/current characteristics. This architecture presents high reliability, simple design and system flexibility in order to include other power sources. However, to control such a kind of system, a fully automatic energy management system has to be implemented in order to provide the optimal scheduling of the fuel cell operation.

A steady state model describing the FC system operating points has been developed by means of the experimental data

acquired with the implemented test facility. The empirical model can be used to study how to increase the system performances, to simplify the PEM lay-out, to improve its design and to identify the optimal control strategies.

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